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α -Helix E of Spo0A Is Required for σ^A - but Not for σ^H -Dependent Promoter Activation in *Bacillus subtilis*

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At the onset of endospore formation in *Bacillus subtilis*, the DNA binding protein Spo0A activates transcription from two types of promoters. The first type includes the *spoIIIG* and *spoIIIE* promoters, which are used by σ^A -RNA polymerase, whereas the second type includes the *spoIIA* promoter, which is used by RNA polymerase containing the secondary sigma factor σ^H . Previous genetic analyses have identified specific amino acids in α -helix E of Spo0A that are important for activation of Spo0A-dependent, σ^A -dependent promoters. However, these amino acids are not required for activation of the σ^H -dependent *spoIIA* promoter. We now report the effects of additional single-amino-acid substitutions and the effects of deletions in α -helix E. The effects of alanine substitutions revealed one new position (239) in Spo0A that appears to be specifically required for activation of the σ^A -dependent promoters. Based on the effects of a deletion mutation, we suggest that α -helix E in Spo0A is not directly involved in interaction with σ^H -RNA polymerase.

Initiation of endospore formation in *Bacillus subtilis* is controlled by the DNA binding protein Spo0A, which activates transcription from several promoters, including *spoIIIG* (11), *spoIIIE* (17), and *spoIIA* (2, 15), by binding to sites near the –35 region of these promoters. The *spoIIIG* and *spoIIIE* promoters are used by σ^A -RNA polymerase, whereas the *spoIIA* promoter is used by RNA polymerase containing the secondary sigma factor σ^H . Previous studies conducted by Buckner et al. (1) and Hatt and Youngman (4) identified a 14-amino-acid region in the C terminus of Spo0A (from residues 227 to 240) important for activation of Spo0A-dependent, σ^A -dependent promoters. Specifically single-amino-acid substitutions at positions G227, I229, S233, F236, and V240 result in reduced ability to stimulate transcription of σ^A -specific promoters while having no effect on stimulation of σ^H -dependent promoters (1, 4). In addition to these mutations that specifically impair σ^A -dependent promoter activation, Buckner et al. (1) also report that a mutant form of Spo0A (S231F) suppresses the sporulation defect of H359R and several other substitutions in σ^A , again suggesting that the region around residue 231 in Spo0A is important for σ^A -dependent promoter activation. Interestingly, all mutations in Spo0A affecting the ability of σ^A -dependent RNA polymerase to activate transcription cluster in α -helix E, a flexible helix in the C terminus of the protein (7, 18) (Fig. 1). Taken together these results suggest that α -helix E perhaps contacts σ^A -RNA polymerase when bound to promoters to stimulate transcription.

It is not known whether all the amino acid residues in α -helix E that are involved in stimulation of σ^A -directed transcription have been identified or whether any of the amino acids in α -helix E play a direct role in activation of σ^H -RNA polymer-

ase. Therefore, we examined the effects of additional single-amino-acid substitutions and the effects of deletions in α -helix E on activation of σ^A - and σ^H -dependent promoters.

MATERIALS AND METHODS

Bacterial strains and culture media. Routine microbiological manipulations and procedures were carried out by standard techniques as described by Harwood and Cutting (3). The concentrations of antibiotics used for selection on Luria broth or Difco sporulation media (DSM) were 5 μ g/ml for chloramphenicol, 100 μ g/ml for spectinomycin, and 100 μ g/ml for ampicillin. Cultures were grown in Luria broth, and sporulation was induced by nutrient exhaustion in DSM. Competent cells were prepared and transformed by the two-step method as described by Harwood and Cutting (3).

The *B. subtilis* strains used (Table 1) are all derivatives of JH642 and contain the *tpc2* and *phe-1* alleles. Plasmids derived from pCB2 (1) were used for inserting various mutations at the wild-type *spo0A* locus.

In order to create the *spo0A* deletion strain (EUAKB78), the 5'-flanking DNA of *spo0A* was PCR amplified with primers 0AUS5FOR (*Hind*III end) and 0ADS5REV (*Bcl*I end) and was cloned into *Hind*III-*Bcl*I-digested pCB3 (1) to generate plasmid pAK53. pAK53 was linearized with *Sca*I and was transformed into JH642 as previously described by Buckner et al. (1). Chromosomal DNA was isolated from a spectinomycin (100 μ g/ml)-resistant transformant by using the Qiamp DNA Mini Kit (Qiagen Inc., Valencia, Calif.) and was subjected to PCR to determine if the gene replacement of spectinomycin for *spo0A* occurred. The following PCR primers were used in combination, 0AUUS5FOR and SpecREV or 0ADS2REV and SpecFOR, to confirm the allelic replacement of the *spo0A* with the spectinomycin gene.

The QuikChange site-directed mutagenesis kit (Stratagene, La Jolla, Calif.) was used to create mutations in Spo0A that resulted in single alanine substitutions. Briefly, pCB2 was used to create single alanine substitutions from amino acid positions 234 to 239 of Spo0A. The combination of FOR and REV primers listed in Table 2 was used to make the single-amino-acid substitutions, and the resulting plasmids for each mutation were subjected to sequencing by using the 0AUS4FOR and 0A3CREV primers to ensure the presence of the desired mutation.

Overlapping PCR was used to create three different deletions within the coding sequence of Spo0A. In deletion 1, amino acids from positions 225 to 244 were deleted, and in deletion 2, amino acids from positions 233 to 241 were deleted, while in the third class of deletion amino acids from positions 229 to 241 were deleted. In the first round of PCR, the 5' end of the coding sequence (from the starting methionine to either amino acid position S225, S233, or I229) was amplified with forward primer 0AUSFOR in combinations with reverse primer 0ADS3REV, 0ADS4REV, or 0ADS5REV. This generated three PCR products that contained overlapping complementary regions at their 3' end to primers

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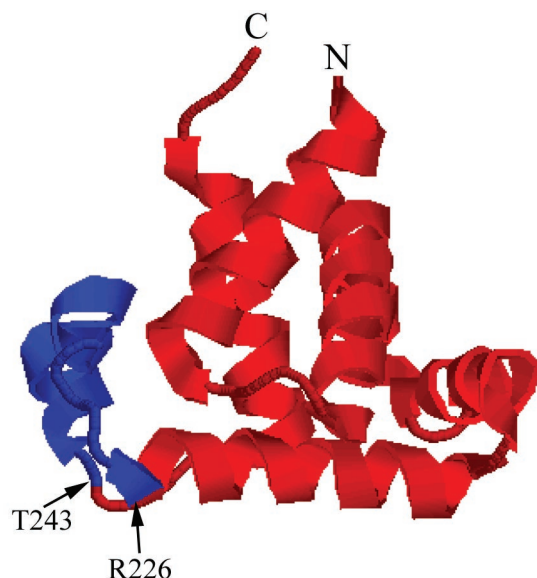


FIG. 1. Ribbon diagram of the C-terminal, DNA binding domain of Spo0A. The structure of the *Bacillus stearothermophilus* Spo0A is based on coordinates from Lewis et al. (7) and is generated by using RasMol version 2.7.1.1. The α -helix E is colored blue, and the rest of the structure is red. Regions of the helix deleted in *B. subtilis* Spo0A are delineated by the numbered amino acid positions. Amino acid positions R226 and T243 correspond to amino acid positions R218 and S235 in *B. stearothermophilus* Spo0A, respectively.

0AUS2FOR, 0AUS3FOR, and 0AUS4FOR primers, respectively. In the second round, the 3' end of the Spo0A coding sequence (from amino acid positions A244 or S241 to S267) was amplified with primer 0AUS2FOR, 0AUS3FOR, or 0AUS4FOR in combination with 0ADS6REV. In the third step, the products of the first- and second-round primers were combined and reamplified with outer primers 0AUSFOR and 0ADS6REV. This gave PCR products that now contained the entire *spo0A* sequence with deletions incorporated within them. The PCR products obtained from the third round were digested with *Bcl*I and

TABLE 1. Bacterial strains used in this study

<i>B. subtilis</i> strain or bacteriophage	Genotype	Source or reference
Strains		
JH642	<i>trpC2pheA1</i>	J. Hoch
EUAKB18	<i>Wtspo0A-spec</i>	This work
EUAKB78	$\Delta spo0A::spec$	This work
EUAKB56	S234A-Spo0A	This work
EUAKB55	L235A-Spo0A	This work
EUAKB57	F236A-Spo0A	This work
EUAKB54	G237A-Spo0A	This work
EUAKB20	Y238A-Spo0A	This work
EUAKB19	Y238K-Spo0A	This work
EUAKB21	Y238D-Spo0A	This work
EUAKB58	T239A-Spo0A	This work
EUAKB38	Spo0A Δ 1	This work
EUAKB39	Spo0A Δ 2	This work
EUAKB40	Spo0A Δ 3	This work
EUAKB82	Suppressor to EUAKB38, V8A+Spo0A Δ 1	This work
Bacteriophages		
SP β <i>spoIIg-lacZ</i>		10
SP β <i>spoIIA-lacZ</i>		16
SP β <i>abrB-lacZ</i>		19

TABLE 2. Oligonucleotides used for PCR, sequencing, and mutagenesis

Name	Sequence (5'-3')
0AUS5FOR	.....CCCAAGCTTAACAGAAAATCAAAACGAGCTG
0ADS5REV	.....GCGTGATCACACGTTTCTTCTCCCAAAATG
0AUS5FOR	.....GGATGCTGTCAGAAGCAGGAATC
SpecREV	.....CCACTCTCAACTCCTGATCC
0ADS2REV	.....CTTAGTCGGCTACCGCTGTG
SpecFOR	.....GGATCAGGAGTTGAGAGTGG
0AUS4FOR	.....CATTGGGGAGGAAGAAAC
0A3CREV	.....CGCGGATCCTTAAGAAGCCTTATGCTC
0AUSFOR	.....AAGCAAGCTTACTGCCGAGTTTCCGGA
0ADS3REV	.....AGCTTTGCTCCGCGCTCCATGCCACTTCAATTGC
0ADS4REV	.....TGTCATGCTGCTCCGGAATGGAATCAATGTTTCC
0ADS5REV	.....TGTCATGCTTACCTCCAATGTTTCTCTGCTCCATGC
0AUS2FOR	.....TGGAGCGGCGGAGGCAAGCTAAACCTACCAACAGTG
0AUS3FOR	.....TCCATTTCGGGAGGCAGCATGACAAAAGCTAAACC
0AUS4FOR	.....GGAACATTGGAGGTAGCATGACAAAAGCTAAACC
0ADS6REV	.....TCTAGGGTTGATCATGCTTCGTGATCC
S234AFOR	.....TGATTCATTTCGCGGTTGTTGGTTATAC
S234AREV	.....GTATAACCAACAACGCGGAATGGAATCA
L235AFOR	.....GATTCATTTCCTCGGCGTTTGGTTATAC
L235AREV	.....CAGTATAACCAACGCCGAGGAATGGAATC
F236FOR	.....CATTTCCTCGTTGGCTGTTTACTGTGTCAGC
F236AREV	.....GCTGACAGTATAACGAGCAACGAGGAATG
G237AFOR	.....CATTTCCTCGTTGTTTGGTTTACTGTGTCAGCATG
G237AREV	.....CATGCTGACAGTATAAGCAACAACGAGGAAT
Y238AFOR	.....CCATTTCCTCGTTGTTTGGTGTACTGTGTCAGCATGAC AAAAGC
Y238AREV	.....GCTTTTGTGTCAGTGTGACAGTAGACCAACAACGAGG AAATGG
Y238DFOR	.....CCATTTCCTCGTTGTTTGGTGATGTGTCAGCATGAC AAAAGC
Y238ADREV	.....GCTTTTGTGTCAGTGTGACAGTATACCAACAACGAGG AAATGG
Y238KFOR	.....CCATTTCCTCGTTGTTTGGTAAACTGTGTCAGCATGAC AAAAGC
Y238KREV	.....GCTTTTGTGTCAGTGTGACAGTTTACCAACAACGAGG AAATGG
T239AFOR	.....CGTTGTTTGGTTATGCTGTGTCAGCATGACAAAAG
T239AREV	.....CTTTTGTGTCAGTGTGACAGCATAACCAACAACG

*Hind*III and were cloned into *Bam*HI-*Hind*III-digested pCB3, thus giving rise to three different integrational vectors (pAK21, pAK22, and pAK23). To confirm that the deletions were in frame with the coding sequence, plasmids pAK21, pAK22, and pAK23 were sequenced with primer 0A3CREV.

Each mutant derivative of pCB2 was linearized with *Sca*I and was transformed into competent JH642. Chromosomal DNA was prepared from spectinomycin-resistant colonies and was subjected to PCR with primer sets 0AUSFOR and SpecFOR and 0ADSREV2 and SpecREV to indicate that recombination occurred at the correct location on the chromosome. The resulting PCR fragment was then sequenced with 0AUS4FOR and 0A3CREV to confirm the presence of the desired mutation.

In order to measure the effects that Spo0A mutations had on σ^A - and σ^H -RNAP holoenzyme-transcribed promoters, each of the mutant strains was transduced with an SP β lysate containing either an *spoIIA-lacZ*, *spoIIg-lacZ*, or *abrB-lacZ* reporter, as previously described by Henriques et al. (5). All strains used are listed in Table 1.

Sporulation assay. Sporulation was induced by medium exhaustion in DSM as described previously (12). Sporulation efficiency was determined in 30-h cultures as the total number of heat-resistant (80°C for 20 min) CFU compared with the total number of CFU before heat treatment. Data presented were from representative experiments. Similar results were obtained in at least three independent experiments.

β -Galactosidase activity. Cultures were grown in duplicate in DSM with the appropriate antibiotics to initiate sporulation. Two 300- μ l aliquots of each culture were collected, i.e., one to measure the optical density and the other to assay for β -galactosidase activity. Enzymatic activity is reported in Miller units (5).

In vivo mutagenesis with EMS. The strain to be mutagenized was plated on DSM agar containing the appropriate antibiotics and was incubated for 36 h at 37°C. A sterile piece of filter paper with 3 drops of ethyl methanesulfonate (EMS) (1.7 mg/ml; Sigma) was placed at the center of the plate. The cultures

TABLE 3. Effects of alanine substitutions for amino acid residues 234 to 239 within wild-type *B. subtilis* Spo0A

Strain	Genotype	No. of CFU (ml ⁻¹) ^a	No. of heat-resistant spores (ml ⁻¹) ^b	β-Galactosidase activity (Miller units) ^c for:		
				<i>IIG-lacZ</i>	<i>IIG-lacZ</i>	<i>abrB-lacZ</i>
EUAKB18	Isogenic wild type	9 × 10 ⁸	6 × 10 ⁸	87 ± 6	26 ± 3	20 ± 3
EUAKB78	Null	15 × 10 ⁸	No spores	14 ± 0	9 ± 0.11	265 ± 31
EUAKB56	S234A	8 × 10 ⁸	11 × 10 ⁸	219 ± 11	16 ± 2	31 ± 9
EUAKB55	L235A	5 × 10 ⁸	4 × 10 ⁸	165 ± 22	23 ± 0.1	39 ± 8
EUAKB57	F236A	9 × 10 ⁸	10 × 10 ³	37 ± 3	7 ± 0.5	37 ± 10
EUAKB54	G237A	15 × 10 ⁸	7 × 10 ⁸	213 ± 5	23 ± 0.6	34 ± 1
EUAKB20	Y238A	6 × 10 ⁸	3 × 10 ⁸	513 ± 72	30 ± 2	20 ± 1
EUAKB58	T239A	5 × 10 ⁸	15 × 10 ⁴	127 ± 19	14 ± 0.4	19 ± 5

^a Cultures were grown for 30 h at 37°C, serially diluted, and plated for counting.

^b Same cultures were heated for 20 min at 80°C, serially diluted, and plated for counting.

^c β-Galactosidase activity of the promoter fusions at 3 h after the end of the stationary phase. Shown is the average from two experiments.

were further incubated for 24 h at 37°C, and the plates were exposed to chloroform vapor for 15 min to kill all nonsporulating cells. The plate contents were incubated for 48 h at 37°C to allow any spores to germinate. Colonies were seen only with the EMS-mutagenized strain EUAKB38 carrying the deletion 1 derivative of Spo0A. Single colonies (15) were picked from DSM plates and were streaked out to Luria broth plates. Chromosomal DNA was prepared from each of these colonies and was used to transform EUAKB11 (wild type-Spo0A; *spoIIA-lacZ*). The transformants were selected for spectinomycin resistance (the marker for the *spo0A*) and were scored for blueness. These transformations revealed that all the suppressor mutations were linked to the *spo0A* gene.

Chromosomal DNA was prepared from each of 15 strains, and the *spo0A* gene was amplified with primers 0AUS4FOR and 0A3CREV. The resulting PCR product was sequenced with primers to identify the position of the new mutation. All sequencing was done at the Emory Core DNA facility (Emory University, Atlanta, Ga.).

RESULTS AND DISCUSSION

Identification of a new position in α-helix E of Spo0A that is required for σ^A-dependent promoter activation. To determine whether additional amino acids in α-helix E are involved in stimulation of σ^A-dependent promoters and if any of these amino acids play a role in stimulation of σ^H-directed transcription, we isolated mutants that produced single alanine substitutions at each position from 234 to 239 in Spo0A. To assay the effects of the single alanine substitutions in Spo0A on expression of Spo0A-regulated promoters, we transduced these mutants with specialized SPβ phage lysates that carried either fusions of *spoIIG-lacZ* (an Spo0A-activated, σ^A-dependent promoter), *spoIIA-lacZ* (an Spo0A-activated, σ^H-dependent promoter), or *abrB-lacZ* (an Spo0A-repressed promoter). We also isolated isogenic transductants of a strain containing a spectinomycin marker linked to the wild-type *spo0A* allele and of a strain carrying a deletion of the *spo0A* locus. All of the strains were cultured in DSM, and the accumulation of β-galactosidase was monitored during endospore formation. Three of the single alanine substitutions (L235A, G237A, and Y238A) had little effect on the expression of *spoIIG-lacZ* (Table 3). These mutants also formed heat-resistant spores at frequencies similar to that of the wild-type strain (Table 3). However, substitution of mutations F236A and T239A resulted in reduced expression of *spoIIG-lacZ* and spore formation (Table 3; Fig. 2). The T239A substitution caused increased expression of *spoIIA-lacZ* and had little to no effect on expression of *abrB-lacZ* (Table 3; Fig. 2). These latter results indicate that T239A replaced Spo0A functions as least as well as wild-type Spo0A in activating *spoIIA* transcription and in repressing *abrB* tran-

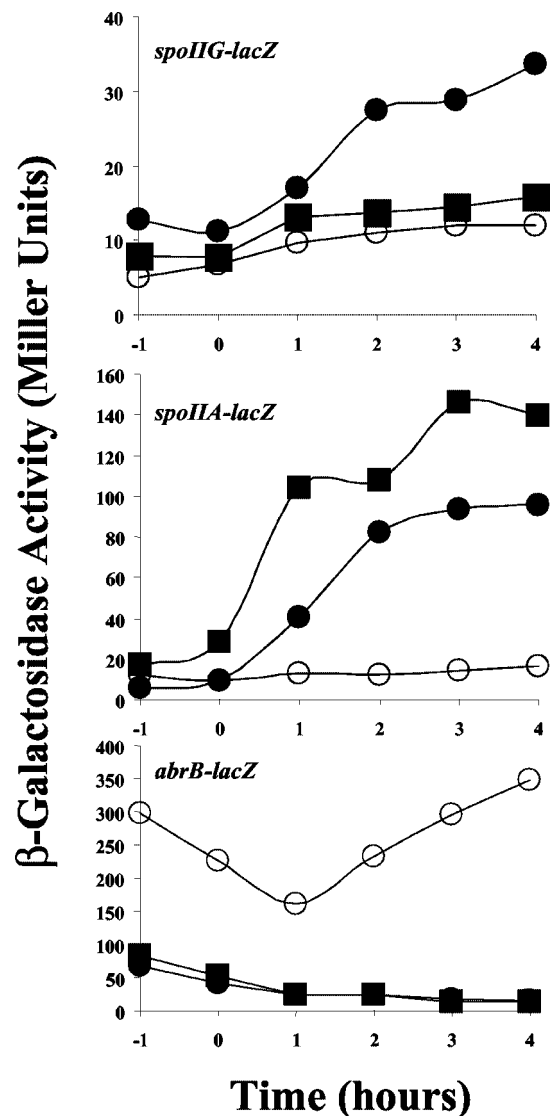


FIG. 2. Effect of substitution T239A on the expression of *spoIIA-lacZ*, *spoIIG-lacZ*, and *abrB-lacZ* transcriptional fusions. DSM cultures of each transduced strain, i.e., EUAKB18 (wild-type-0A ●), EUAKB58 (T239A-0A ■), and EUAKB78 (Null-0A ○), were harvested at hourly intervals beginning at about 1 h before the end of the exponential growth, which is indicated as 0 on the time scale. The collected samples were assayed for β-galactosidase activity indicated in Miller units.

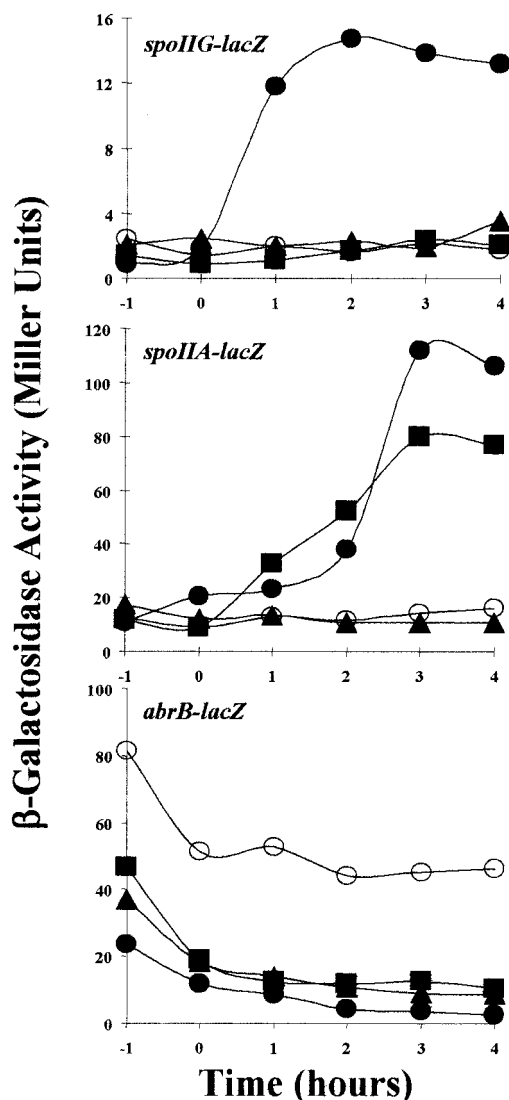


FIG. 4. Effect of deletion mutant Spo0A alleles on expression of *spoIIA-lacZ*, *spoIIG-lacZ*, and *abrB-lacZ* transcriptional fusions. DSM cultures of each transduced strain, i.e., EUAKB18 (wild-type-0A ●), EUAKB38 (Spo0A Δ 1 ▲), EUAKB82 (Spo0A Δ 1+V8A ■), and EUAKB78 (null-0A ○), were harvested at hourly intervals beginning at about 1 h before the end of the exponential growth, which is indicated as 0 on the time scale. The collected samples were assayed for β -galactosidase activity indicated in Miller units.

gene (14). However, the small decrease in accumulation of the Spo0A deletion derivatives probably played no role in the reduction of Spo0A-dependent promoter activation. Immunoblot analyses showed that the V8A substitution did not substantially increase the accumulation of Spo0A (data not shown). Nevertheless, the V8A substitution restored activation of the *spoIIA* promoter by the deletion 1 derivative Spo0A. One possible explanation for these results is that the V8A substitution increases the fraction of the Spo0A that is phosphorylated, which allows the protein to stimulate transcription more efficiently. Consistent with this hypothesis is the observation by Stephenson et al. (13) that N12 of Spo0A is critical for interaction with the Spo0E phosphatase. Two highly conserved aspartate residues, D10 and D11, that form part of the acid

pocket at the phosphorylation site are located between N12 and V8 (6). Therefore, it is possible that the V8A substitution may reduce interaction with the Spo0E phosphatase, resulting in higher levels of Spo0A phosphorylation. The equivalent residue of Spo0A V8 is normally a hydrophobic residue in response regulator receiver domains and lies in the first element of the secondary structure, a β -strand that contributes to the positioning of the β 1- α 1 loop containing the residue D10-N12, and so this is our preferred explanation.

Other possible mechanisms by which the V8A substitution restores activation of σ^H -directed transcription by the α -helix E deletion derivative of Spo0A would include creation of an interaction between the N-terminal domain of Spo0A and RNA polymerase that compensates for an interaction with RNA polymerase that was lost upon deletion of α -helix E or a model in which the V8A affects interaction between the N- and C-terminal domains of Spo0A. We cannot eliminate the former model, but it seems unlikely that substitution of valine for alanine, which effectively removes side chain volume, would establish a new interaction between proteins and seems likelier that the alanine substitution would eliminate an interaction, such as between Spo0A and Spo0E. We also cannot completely eliminate the latter model. However, if the V8A substitution affects the interaction between the C- and N-terminal domains of Spo0A, the effect on the conformation of the C-terminal domain would likely be very small. This effect would not likely be great enough to compensate for the absence of α -helix E if this helix plays a direct role in stimulating σ^H -RNA polymerase. Therefore, we conclude that α -helix E in Spo0A probably is not directly involved in interaction with σ^H -RNA polymerase. If α -helix E does not interact with σ^H -RNA polymerase, then another region of Spo0A probably interacts with σ^H -RNA polymerase. Presently the best candidate for a region of Spo0A that interacts with σ^H -RNA polymerase is at the extreme C terminus, where amino acid substitutions at positions 257, 258, and 260 have been shown by Rowe-Magnus et al. (9) and Perego et al. (8) to reduce activation of the σ^H -dependent promoter *spoIIA*. However, as Rowe-Magnus et al. (9) discuss in their paper, they could not eliminate an indirect role for this region in activation of σ^H -dependent promoters.

ACKNOWLEDGMENT

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